Development and Deployment of an Ultrasonic Groundwater Seepage Meter: A Reliable Way to Measure Groundwater Seepage

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Abstract- ***Submarine groundwater discharge can significantly influence the near shore transport of chemicals into surface waters. Quantification of the sources and rates of such discharge is critical to development of management strategies. Quantification requires a groundwater seepage meter that provides continuous measurements at high resolutions over an extended period of time. An ultrasonic flow meter has been developed for such measurements in the subsurface environment. Connected to a collection funnel the meter houses two piezoelectric transducers mounted at opposite ends of a cylindrical flow tube. By monitoring the perturbation of fluid flow on the propagation of sound waves inside the flow tube, the ultrasonic meter can measure both forward and reverse fluid flows in real time. Laboratory and field calibrations show that the ultrasonic meter can resolve groundwater discharge on the order of 0.1 um/s and is sufficiently robust for deployment in the field for several days. A parallel effort has applied a direct contact resistivity probe used by divers to identify areas of groundwater seepage. These tools have been applied to identify areas of groundwater seepage. These tools have been applied to quantify ground water seepage and associated contaminated loads from landfills, Superfund/industrial sites, and agricultural sites and to develop nutrient budgets for computer modeling. These techniques have been used in deployments with the US Navy, Battelle Labs, the Suffolk County Health Services and the United Nations. Equipment has now been developed that integrates this meter with an automated sampling device that can be deployed for 4 days and collect seepage flow regulated samples.***

I. INTRODUCTION

Groundwater can flow directly into the sea through porous rocks and sediments. It seeps from unconfined aquifers into the near shore or is discharged from confined aquifers found underneath continental shelves further from shore. Previous estimates of this submarine groundwater discharge (SGD) worldwide range from 0.01 to 10% of surface-water runoff [1]. In bays and estuaries the input of freshwater can be particularly large. [2] found that 10 - 20% of the water entering the Great South Bay of New York is groundwater discharge, and in lakes that percentage can be much higher [3,4] inferred from measurements of enriched ^{226}Ra in the coastal waters of the South Atlantic Bight and mass balance calculations, that SGD can contribute up to 40% of the total river flow into the ocean. Such discharge can have a substantial effect on near-shore transport mechanisms and therefore a major influence on the flux of chemicals into the bays and oceans.

In near-shore marine environments, the key input for SGD is probably the discharge from land to ocean induced by hydraulic gradient and regulated by hydraulic conductivity in the terrestrial aquifer (Figure 1). However, significant contribution to the SGD in coastal environments may also derive from groundwater circulation and oscillating flow induced by wave setup and tide [5,6]. A better quantification of the sources and rates of these submarine discharges has been difficult because there is a paucity of direct measurements with sufficient resolutions of the seepage rate and salinity. Furthermore, the *in situ* measurements have been quite limited in spatial and temporal coverage. Indirect inference of the discharge is also difficult because of insufficient information on hydraulic gradients and transmission coefficients (transmissivity) along the world's coasts.

Conventionally, groundwater seepage has been measured using the open, cut-off end of a 55-gallon steel drum that is pushed into the bottom sediment[7,8]. The groundwater head of the adjacent upland area induces the fresh groundwater to seep into the drum funnel, and a plastic bag attached to a tube in the top of the drum catches the seepage. After a period of time, the bag is removed from the tube and the cumulative discharge is measured. This conventional bag method has been successfully applied in various hydrogeologic settings, including lakes, reservoirs, rivers, estuaries, and coasts. Subsequent studies have shown that this method has several limitations [9,10,11,12,13,14]. First, it is cumulative and therefore cannot provide information on the temporal evolution of seepage. Second, it cannot accurately measure reverse flow or resolve small fluctuations in seepage (such as those induced by tides or wave action). Third, measurement errors can readily arise from frictional resistance and head

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 SEP 2003	**N/A**	**-**

4. TITLE AND SUBTITLE
Development and Deployment of an Ultrasonic Groundwater Seepage Meter: A Reliable Way to Measure Groundwater Seepage

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cornell Cooperative Extension of Suffolk County 423 Griffing Ave Riverhead, New York, 11901, USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002146. Oceans 2003 MTS/IEEE Conference. Held in San Diego, California on September 22-26, 2003. U.S. Government or Federal Purpose Rights License, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**9**	

loss along the internal boundary of the meter, attachment tube and the reservoir bag, as well as anomalous, short-term influx of water after the plastic bags has been attached to the seepage meter.

Accordingly, it is desirable to develop a robust seepage meter that can overcome such measurement limitations and provide continuous SGD measurement down to relatively low rates. Researchers [15] developed a remotely deployed meter. However, it requires a large vessel and cannot be used in shallow water depths. Other researchers [11] developed a seepage meter that can continuously measure seepage rates by a thermal perturbation technique. An analogous technique was recently employed by [17} to develop a meter that can measure the 3-dimensional flow velocity vector in unconsolidated material.

In recent years, ultrasonic flow meters have been developed to measure relatively low flow rates in many engineering and materials science applications. These flow measurements are based on the perturbation of sound speed in a fluid induced by flow motion. By taking advantage of such advancements in ultrasonic technology we recently developed a seepage meter for the continuous measurement of SGD at rates as low as 0.1 μm/s. Simultaneous measurements of the sound speed and temperature also allow us to constrain the salinity of the SGD, and thereby infer the sources from which it is derived. The ultrasonic meter can measure reverse flow as well, and it has been deployed at various coastal sites on Long Island, New York to continuously acquire data over a duration up to 5 days. The data elucidate subtle fluctuations in SGD that correlate with tidal loading. We will describe below the design and principle of the ultrasonic seepage meter, its calibration in the laboratory and field, and representative sets of data from various coastal setting.

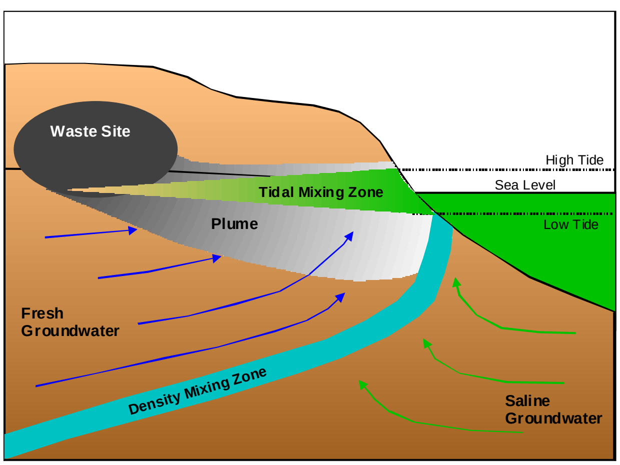

Fig. 1. Conceptual representation of the coastal contaminant migration process and associated groundwater-surface water interaction.

II. METHODS

A. Design and Principle of Seepage Measurement System

The SGD is captured by a steel collection chamber with a square cross-section that is placed on the seabed (Fig. 2). In our prototype meter, the sides of this funnel are each 0.46 m long (corresponding to a capture area $A = 0.21$ m^2). The captured SGD is directed via Tygon tubing through an ultrasonic flow tube.

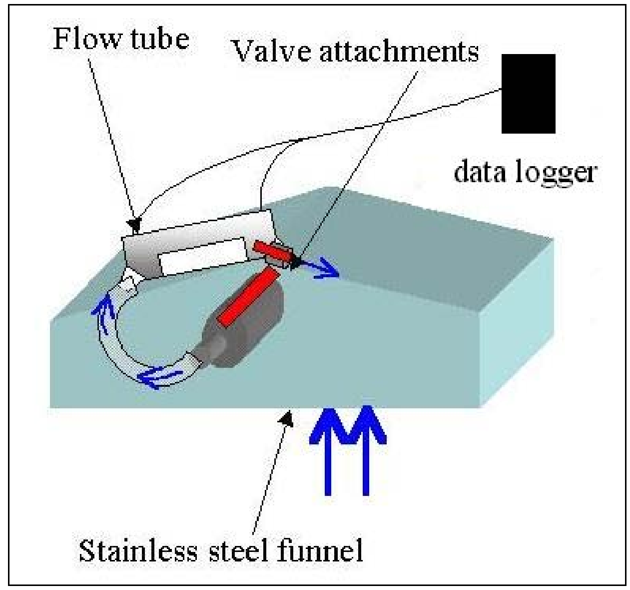

Fig. 2. Ultrasonic seepage system

The ultrasonic flow tube houses two piezoelectric transducers mounted at opposite ends of a cylindrical flow tube (of diameter d = 9.5 mm and length L = 200.2 mm). The transducers continually generate bursts of ultrasonic signals from one end of the meter to the other end (Fig. 3). Typically ~400 bursts are transmitted per second, and each burst is made up of ~40 periodic waves with a frequency of 1.7 MHz. Arrival of the ultrasonic signals is continuously monitored by the piezoelectric transducers.

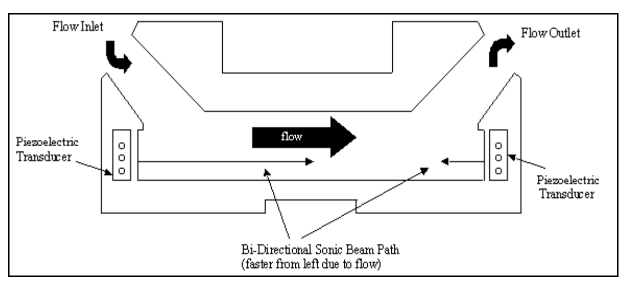

Fig. 3. Ultrasonic flow tube

In a static fluid, the sound speed V is sensitively dependent on temperature and salinity. If the fluid flows with a velocity v, then travel time for the upstream

propagation of sound waves against the flow direction is prolonged relative to that for downstream propagation (Fig. 4).

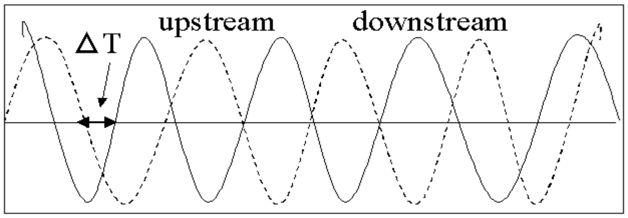

Fig. 4. Propagation of sound waves

Specifically, the upstream and downstream travel times are given by $T_{up} = L/(V - v)$ and $T_{down} = L/(V + v)$, respectively. Combining these two equations to solve for the flow velocity, we arrive at

$$v = \frac{L}{2\,T_{up}\,T_{down}}(T_{up} - T_{down}) \text{ . (1)}$$

If the fluid flow is so slow that $v << V$, and if the fluctuations of temperature and salinity are relatively small (so that the perturbation of sound speed is negligible), then $v \propto T_{up} - T_{down}$.

Since equation (1) is used in the ultrasonic meter to determine the fluid flow velocity v in the tube, it is critical to resolve the travel time difference $T_{up} - T_{down}$ down to a nanosecond. The characteristics of the piezoelectric transducers and ultrasonic signals were chosen so that minimal attenuation of the signals would occur in the flow tube. The signal-to-noise ratio is also enhanced by using tens of cycles in a single burst and averaging the repeated measurements. The velocity value calculated using equation (1) is then adjusted by a Reynolds compensation factor (which typically is relatively small) which accounts for the fluid velocity and flow variation across the parabolic laminar flow profile during turbulent or transitional flow periods. The extremely low flow rates in the flow tube produce mostly laminar flow conditions and require only very small adjustments. This adjusted value of the flow velocity v is then multiplied by the areal ratio $(\pi d^2/4)/A$ to give the specific discharge q from submarine groundwater. The data logger can be programmed to acquire the SGD data at frequencies that range from once per second to once per day.

B. Calibration of Ultrasonic Meter and Funnel System

The ultrasonic seepage meter and funnel collection system was developed at Cornell Cooperative Extension's marine laboratory at Cedar Beach, Long Island, New York. Prior to deployment in the field, a series of calibration exercises were performed at Suffolk County's Bureau of Water Resources shop facility in Yaphank, New York. A bench test of the flow tube and data logger system was first performed, followed by tests to determine funnel resistance. Finally, a test tank calibration was performed on the complete seepage system.

In the bench test, the flow tube was clamped in place while water flows from a constant- head tank to the flow tube via Tygon tubing (of internal diameter 0.99 cm). The approximately steady flow rate through the ultrasonic flow tube was controlled by a pipette valve on the discharge tube. After the transient flow had stabilized a calibration test was run under steady flow condition for 5 minutes and repeated. The water discharged from the flow tube was captured in a graduated cylinder. The cumulative discharge divided by time gives average discharge rate, while the ultrasonic meter provides continuous measurement of the rate as a function of time.

Previous studies [2,10,14,5] have documented SGD rates ranging from < 1 μm/s to 15 μm/s. Since a funnel capture area $A = 0.21$ m^2 was chosen in this study, the discharge in the flow tube of the seepage meter that corresponds to this expected range is 0.2 - 3 cm^3/s (with an average flow velocity of $v = 3 - 42$ mm/s). Our calibration results are compiled in Figure 5. The mean and standard deviation of the ultrasonic measurements are both displayed. There is excellent agreement between the two independent measurements of flow rate within the range of 0.05 - 3 cm^3/s. At elevated flow rates, the seepage meter data are somewhat lower than the average discharge inferred from cumulative measurement over time, possibly due to incipient development of turbulence in the flow tube.

A second series of calibration tests were conducted to study possible influences of funnel restriction on the discharge measurement. A cubic fiberglass test tank (with linear dimension of 121 cm) was constructed.

The bottom of the funnel was sealed with an impermeable barrier, and specific discharges into and out of this funnel were simultaneously measured with the funnel and meter both immersed in the tank. A control experiment was initially carried out to determine any flow restriction associated with the flow tubes. Two flow tubes were connected in series and immersed in the test tank. The control test revealed that no flow restriction existed in

the flow tubes and that both flow tubes recorded identical flow rates within the range of interest. One of the ultrasonic flow tubes was then attached to the funnel inlet hose and the second was attached to the outlet of the funnel. The flow rates (ranging from 0.05 to 13 cm^3/sec) were controlled by a constant-head tank. The calibration results are presented in Figure 5. The funnel collection system show negligible impedance of flow until the rate exceeded 3.5 cm^3/sec, and at elevated flow rates up to 5 cm/sec the discrepancy was <5%.

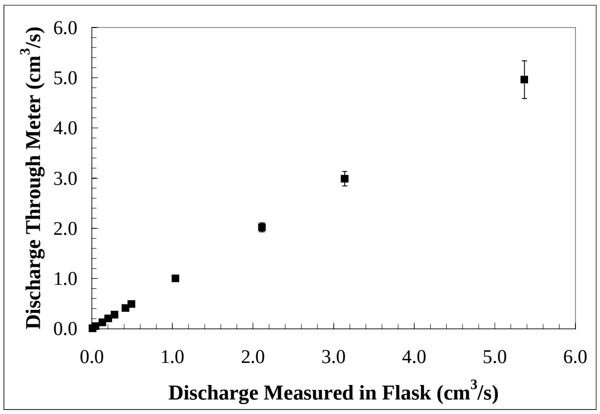

Fig 5-Calibration Results

The final series of calibration tests were performed in a cubic test tank as illustrated in Figure 6. The bottom of the tank was filled with grade-2 gravel pack material and fine-to-medium sand. To uniformly distribute the water that was discharged at the bottom of the gravel layer, the influx from the constant-head tank was supplied through a screened manifold buried 20 cm beneath the surface. The manifold was constructed of 3/4-inch PVC pipe with the bottom section made up of slot-10 PVC screen material. Flow to the manifold was controlled by a needle valve in the discharge hose of the constant-head tank.

The collection funnel was embedded 10 cm into the sand layer to ensure a tight seal (see Figure 6). One end of the flow tube of the seepage meter was attached to the discharge fitting of the funnel with a 20-cm length of Tygon tubing. Water that had percolated through the gravel and sand layers was captured by the funnel and flowed into the seepage meter from this entrance. The exit end of the flow tube had two tubings attached. One of them was connected to a graduated cylinder that measured the cumulative discharge from the exit end of the ultrasonic flow meter. In addition, a 100-cm length of tubing exited the test tank at the surface through a bulkhead fitting. This drainage system was to inhibit the development of hydraulic gradient (and head resistance) in the calibration tank.

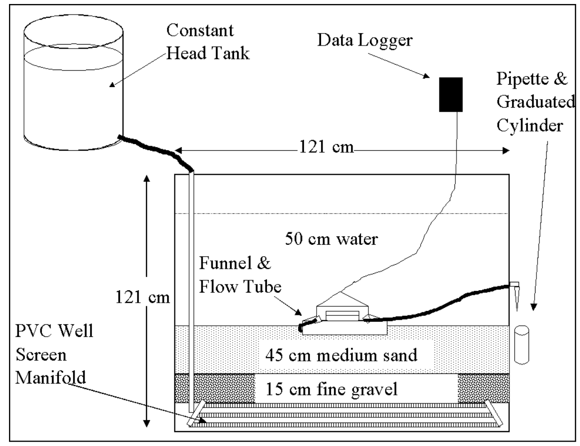

Fig. 6. Calibration tank

Constant flow rates (ranging from 0.05 to 6 cm^3/sec) were applied to the seepage system and continuous measurements of the flow rate were made using the ultrasonic meter. The calibration process was repeated three times for each flow rate. The mean values are presented in Figure 7. Over the range of 0.05 to 2 cm^3/sec the mean flow rate (inferred from the cumulative discharge over time) was bracketed by the ultrasonic data which had relatively small scatter at a given flow rate.

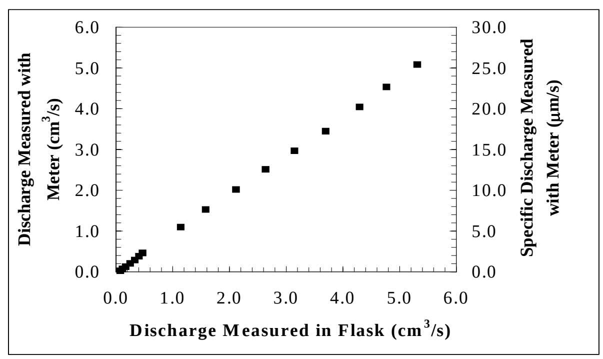

Fig. 7. Test Tank Calibration Results

At elevated flow rates (2 - 5 cm^3/sec) the ultrasonic data were somewhat lower than the mean flow rate (with a discrepancy of <5%), possibly due to flow resistance and turbulence in the funnel or seepage meter tube. It should be noted that the flow rate 0.05 - 5 cm^3/sec corresponds to a specific discharge of 0.25 - 25 μm/s from the sand layer that is captured by the funnel. The term specific discharge introduced here refers to seepage flow per unit area of sediment surface and will be used to throughout this paper to refer to seepage flow from this system. In our calibration tests the lowest flow rate that the constant-head tank can maintain in steady state was 0.05 cm^3/s, but on the bases of field tests to be described later, we believe that the seepage meter can resolve much lower flow rates.

C. Development of Rresistivity- Temp- Pore water sampler-The Trident Probe

To identify potential areas where groundwater is entering the surface water, we have developed the Trident Probe (Fig. 8), a simple direct-push system equipped with temperature, conductivity and water sampling probes. Contrast in temperature and conductivity between surface water and groundwater are used to determine likely areas of groundwater impingement. The water-sampling probe can then be used to collect samples for detailed chemical characterization of contaminants.

The temperature sensor consists of a customized SeaBird SBE 38 digital oceanographic thermometer with a ruggedized, 60 cm long titanium probe. The sensor has a measurement range of -5 to +35 °C at an accuracy of 0.001 °C, and a resolution of 0.00025 °C. The sensor response time is about 500 milliseconds. The sensor housing is titanium with a depth rating of 10,000 meters. Real-time temperature data is transmitted from the unit in ASCII for mat via RS-232 at a frequency of about 2 hertz. Areas of groundwater seepage may appear either as warm or cold contrast to the surface water depending on the seasonal and site characteristics. The conductivity sensor utilizes a custom, small diameter, stainless steel, Wenner-type probe, also of 60 cm length. The probe is configured with two pairs of stainless steel electrodes, the outer pair through which a known current is imposed, and the inner pair through which the voltage is monitored. Both pairs of electrodes are coupled through an underwater connecter and cable to a standard, Geoprobe model FC4000 deck unit which controls the outer electrode pair current, monitors the inner electrode pair voltage, and sends the corresponding raw conductivity signal to a laptop computer via RS-232. The laptop is used to apply calibration and temperature corrections to the signal, and record and display the results. The conductivity signal varies primarily as a function of changes in salinity, and secondarily as a function of clay content and porosity (Fig. 9). Areas of likely groundwater seepage are generally associated with low conductivity, either as a result of low salinity, low clay content (high permeability), or both. The water-sampling probe allows interstitial waters to be extracted from the sediment at selected depths up to about 60 cm below the sediment water interface. Porewater is collected by syringe or vacuum pump extraction through a small-diameter stainless-steel probe (see Fig. 8). The probes consist of a length of ¼ in diameter stainless steel tubing fitted with a solid point. On the side of the tube near the tip there is a sample port consisting of a slot covered by a small mesh size (241 um) stainless steel screen

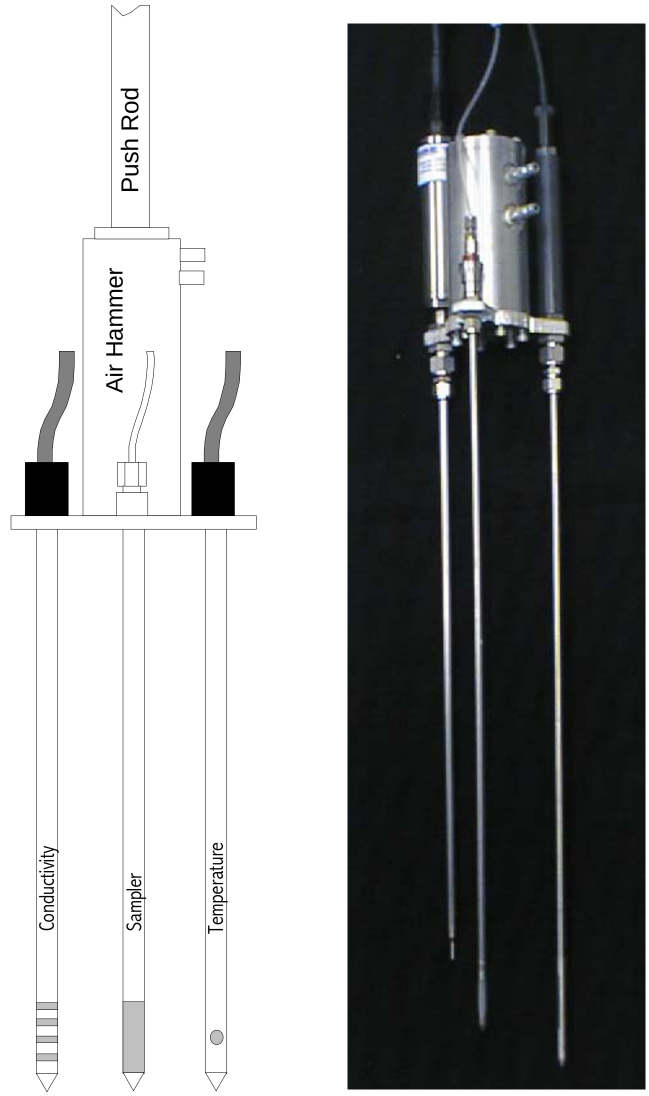

Fig. 8. Schematic and photo of the Trident showing the conductivity, temperature and water sampling probes.

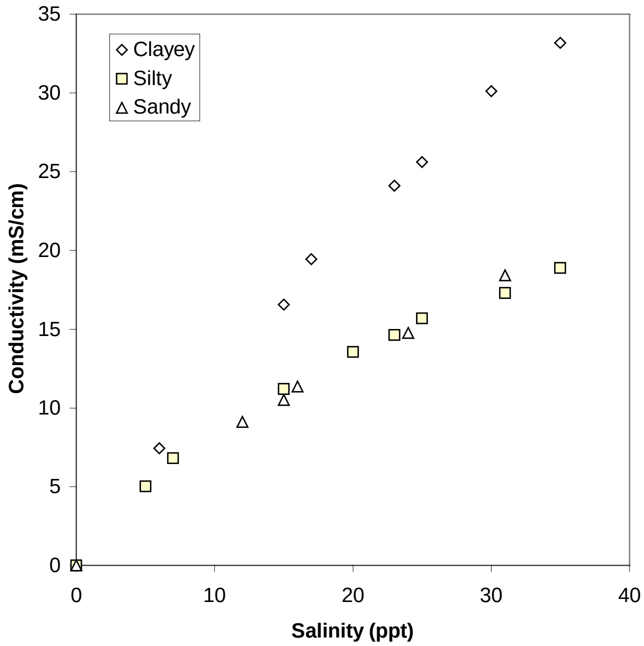

Fig. 9. Response of the Trident conductivity probe to changes in salinity and sediment type.

The three probes are collocated in a triangular pattern with a spacing of about 10 cm on an aluminum mounting base. Coupled to the mounting base is a submersible air-hammer that can be used to assist in driving the probe into the sediment. On the top of the air-hammer is a coupling for a 2 m aluminum push rod that can be sequentially lengthened in 2 m increments to a total length of about 10 m. A bundled cable including the temperature and conductivity signals, Teflon sampling tube, and pneumatic air-hammer hose runs from the probe to the surface. The sensor signals from the temperature probe and the conductivity deck unit are linked to a laptop computer with real time display via a graphical MatLab interface. The GPS is also couple to the laptop to simultaneously record the sampling locations.

In operation, the Trident probe can be deployed in several ways depending primarily on the depth of the site. In very shallow water (0-1 m), the operator simply walks or wades to sampling station, and manually pushes the probe to the desired depth. Experience has shown that the probe pushes easily by hand to a depth of about 30 cm. The air hammer, or a slide hammer can then be used to complete the push if necessary. In water of moderate depths (1-10 m), the probe is easily deployed from a small boat using the push rod in combination with the air-hammer (Fig. 10). It is important that the boat be well anchored to minimize lateral loading on the probe during the insertion. In deeper water (>10 m), the probe can be deployed by diver, or can be attached to a landing frame.

Fig. 10. Deployment of the Trident probe from a small boat using the push rod and air hammer.

III. RESULTS

A .*Field Measurement of Tidal Influence on Submarine Groundwater Discharge*

Following the calibration exercises, our seepage unit was deployed in several coastal areas of known groundwater seepage outcrops in the Long Island area. It was also deployed at Turkey Point, Florida and Cockburn Sound Australia as one of the techniques adopted in the submarine groundwater discharge intercomparison experiment organized by the Scientific Committee on Oceanic Research (SCOR) / Land-Ocean Interactions in the Coastal Zone (LOICZ) Working Group 112. Additionally the meter has been deployed for the investigation submarine groundwater discharge associated with state and federal superfund sites in 5 states. This work was undertaken as a cooperative effort with the US Navy.

Here we will illustrate the quality of our data by representative measurements on the temporal evolution of SGD at two sites located in West Neck Bay, Shelter Island, New York. West Neck Bay is a protected small bay with moderate wave and tidal influences. The groundwater discharge along the submarine seepage face originates from an aquifer of fine-to-medium sands underlain by a base clay at ~ 27m (90 ft) below sea level (Schubert 1998). Due to the hydrogeologic heterogeneity, the hydraulic gradient as well as SGD vary significantly along the submarine seepage face. The ultrasonic flow meter system was deployed offshore along with a continuously logging tide gauge. The data logger and back-up battery were housed in a buoy anchored to shore so that long-term, continuous measurements could be made up to several weeks with minimal risk of damage to the equipment. The battery life of the logger itself is approximately 5 hours

while the back-up battery has a life span of approximately 72 hrs.

Specific discharge and tide stage measured at two different sites of West Neck Bay over a 24-hour period on August 28 and October 16, 1999 are shown in Figure 11a and b.

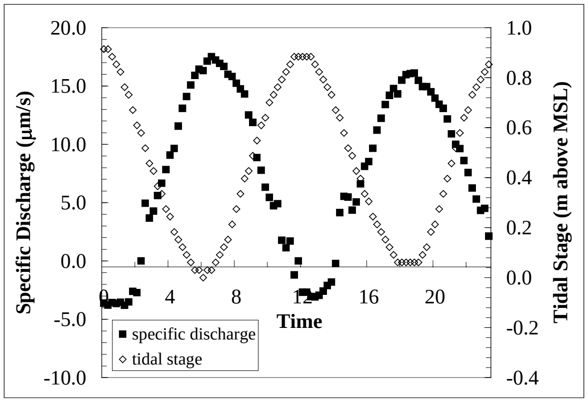

Figure 11a. West Neck Bay Site 1

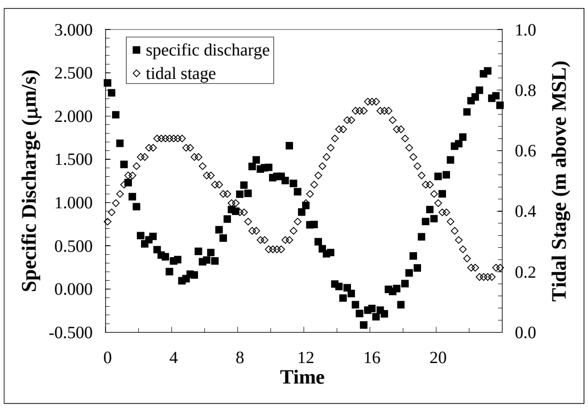

Figure 11b. West Neck Bay Site 2

The ultrasonic data were acquired at a rate of 1/15 min. The discharge at site 1 (Figure 11a) was about seven times that at site 2 (Figure 11b). An overall negative correlation between tidal stage and SGD was observed in both sites. The discharge was inhibited during high tide, and reverse flow (indicated by negative values of specific discharge) occurred as a manifestation of the temporal migration of the interface zone between fresh and salt water. It should also be noted that the maximum (and minimum) in tidal elevation do not correspond exactly to the minimum (and maximum) of specific discharge. In West Neck Bay, the phase lag was ~1½ hours, which was presumably due to the transient fluctuation of the groundwater head in response to tidal loading.

B. Trident Probe Transect

A series of four Trident transects were run between the North Island shoreline (San Diego Bay) and the southern finger of the pier (Figure 12). At each station, conductivity and temperature were determined, and water samples were collected all at the full insertion depth of about 60 cm. Temperature was also measured just above the bottom to evaluate the temperature difference between surface water and subsurface water. Water samples collected at each of the stations were subsequently analyzed for a full suite of VOCs by EPA method 8260B. Transects were carried out during low tides on two different days with each transect required about one hour to complete.

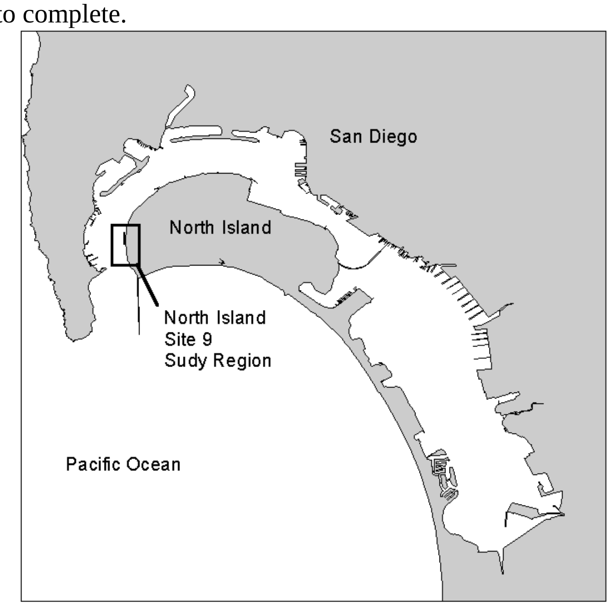

Fig. 12. Map of San Diego Bay and the study region.

Results from the conductivity transect are shown in the contour map of Fig. 13. All values are calibrated and corrected to 25 °C. Lowest conductivity was observed along the shore and northern area of the study region, while higher conductivity was generally found in the mid and offshore regions. However the overall range of conductivity was not large (17-24 mS/cm), suggesting that no significant fresh groundwater plume is present in the area. This finding was supported by salinity measurements on the water samples collected at the site.

Results from the temperature probe are shown in Fig. 14. Contours are plotted as "Delta T", the difference between the near-bottom and subsurface temperatures. Positive values indicate subsurface water that is colder than the near-bottom water. The temperature distribution shows a distinctive pattern with the largest temperature contrast in the middle of the study region, and smaller differences toward the boundaries of the region, with a maximum contrast of about 1.3 °C.

The distribution of 1,1 Dichloroethane (DCE) is shown in Fig. 15. This distribution is representative of several other VOCs detected at the site. The distribution of DCE is similar to that of the temperature contrast, with

highest levels observed in the middle of the study region. Concentrations at the northern and southern extents were generally below detection (<1 ug/L). The highest level observed in the region was about 70 ug/L.

The results show that the Trident probe provides rapid spatial assessment of both groundwater exchange parameters (temperature contrast and conductivity) and contaminant concentrations While there was no clear relationship between the conductivity distribution and the VOC distribution, the temperature contrast at this site appears to provide a good indicator of plume location. Because of the lack of strong freshwater sources on North Island, the variation in conductivity is probably primarily associated with changes in clay content.

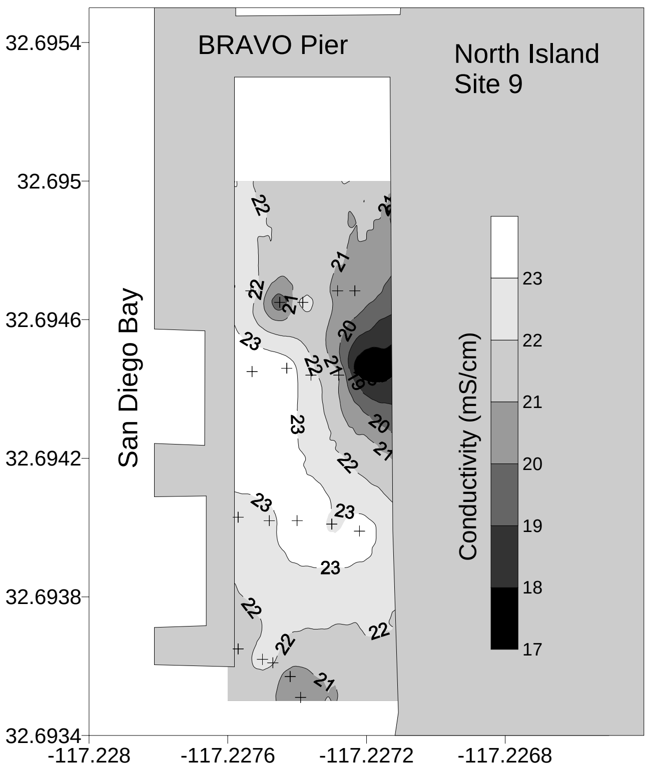

Fig. 13. Spatial distribution of conductivity at 60 cm below the sediment surface.

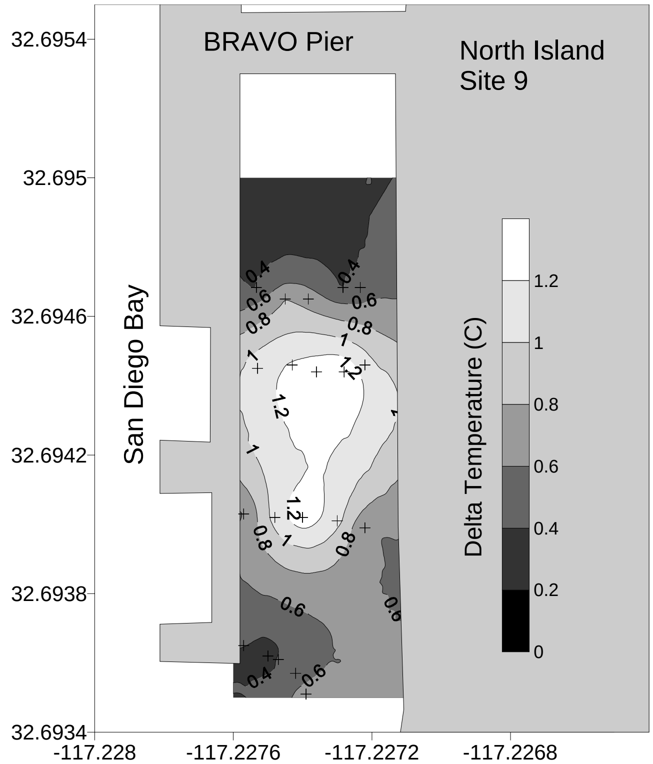

Fig. 14. Spatial distribution of the temperature contrast between near bottom and sub-bottom temperature at 60 cm depth.

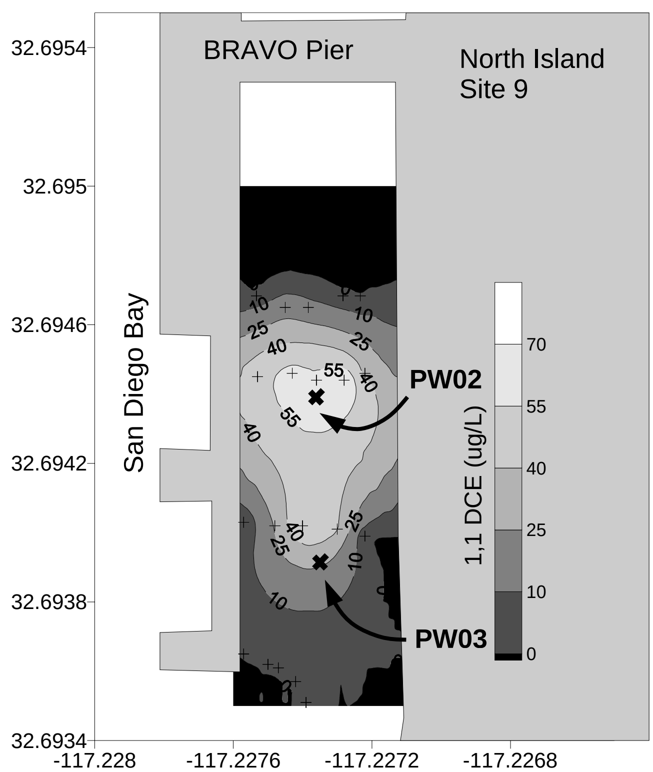

Fig. 15. Spatial distribution of DCE concentration.

IV. CONCLUSIONS

Coastal landfills and hazardous waste sites pose a potential environmental threat to surface water bodies through the exchange of groundwater-borne contaminants. Many of these sites are located adjacent to harbors, bays, estuaries, wetlands, and other coastal environments. Interest in quantifying the exchange between seepage and overlying surface water has increased due to potential impacts resulting from anthropogenic land uses. To identify potential areas where groundwater is entering the surface water, we have developed the Trident Probe, a simple direct-push system equipped with temperature, conductivity and water sampling probes. Contrast in temperature and conductivity between surface water and groundwater are used to determine likely areas of groundwater impingement, and the water sampler is used to collect samples for subsequent chemical analysis. Recent results show that the Trident probe provides rapid spatial assessment of both groundwater exchange parameters (temperature contrast and conductivity) and contaminant concentrations. The Ultrasonic Seepage Meter combines a continuous, direct measurement of groundwater seepage rates using a time transient ultrasonic technique. Recent results from the both methods show that groundwater exchange at coastal sites can be an important process in the transport and fate of dissolved contaminants that emanate from terrestrial waste sites

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